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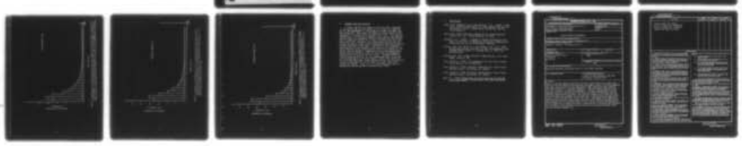

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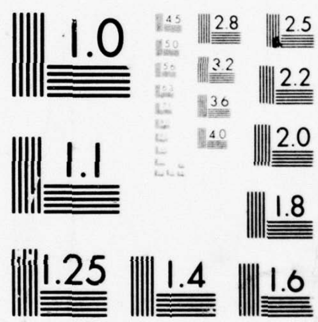

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ARCTIC UNDER-ICE ROUGHNESS.

Leonard A. LeSchack and David C. Chang

Technical Report, 2 Apr 76-15 Nov 77

for

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ABSTRACT

Under-ice profile records obtained in the Arctic Ocean during the winter 1960 cruise of the USS SARGO and the 1960 and 1962 summer cruises of the USS SEADRAGON have been digitized and the Root-Mean-Square (RMS) depths have been computed (The RMS ice depth is a valuable parameter for Arctic acoustic studies as well as a good indicator of under-ice roughness.) Thirteen representative profile segments varying in length from 50-250 miles and taken from the three cruises have been statistically analyzed. This analysis suggests that during the 1960-62 period under-ice roughness varies from place to place during the same period but at a given location does not vary over time. Histograms of ice depths observed across the Arctic Ocean during the above three cruises have been plotted. From these plots it is observed that there is, for this period, 15% open water in the summer and 2% during the winter. Additionally, it is noted that the amount of ice found in each thickness class varies only a few percent between winter and the following summers.

1. Background

Buck et al. (1970) have, as a result of previous experiments, observed that the under-ice surface roughness is an important parameter in the propagation of underwater sound in the Arctic Ocean. The under-ice surface is relevant because in the Arctic Ocean sound is refracted upwards. As a result, acoustic energy travelling any distance in the Arctic Ocean will impinge on the water-ice interface many times along its path. The rougher the interface is, i.e., the more it departs from being a specular reflector, the more scattering will occur, and as a result, the more attenuation there will be. Additionally, they have suggested that acoustic propagation loss over long ray paths (i.e., 500-600 miles) in the Arctic Ocean may be directionally dependent because of anisotropic variations of the under-ice roughness. However, very little quantitative analysis of this possible directional attenuation has been made, since the analysis of under-ice roughness over large areas of the Arctic Ocean has heretofore never been conducted, either with or without concurrent acoustic propagation experiments. Accordingly, only theoretical analysis of the effects of this roughness parameter on directional attenuation of sound has been made (Diachok, 1974).

In our work to date, thousands of miles of Arctic under-ice profiles recorded by nuclear submarines of the U.S. Navy have been analyzed to determine quantitatively the spatial and temporal variations of under-ice roughness for the 1960-62 period. With the development of these new under-ice data, it is expected that further advances in Arctic underwater acoustic propagation may now be possible.

2. Under-Ice Profile Data

In the early 1960's, several submarines of the U.S. Navy made cruises beneath the ice of the Arctic Ocean (Figure 1). Mounted on each of these submarines were several sonar transducers to provide guidance for safe navigation (Figure 2). The sonar data of interest in this study were obtained by beaming sound pulses vertically upward from the submarine and recording the reflections from the water-ice interface. The returning echos were recorded on Edo Sounders, similar to those used by ships for depth recording. These sounders record the profile data on a specially treated paper strip chart driven at constant speed beneath an electrostatic stylus. The stylus moves in such a manner that the outgoing sonar pulse is synchronized with the start of the stylus across the face of the paper. When a returning pulse is received, the stylus is activated and sparks, burning a mark on the strip-chart. In this fashion, an analog profile of the under-ice surface is drawn, with much vertical exaggeration, as the submarine cruises beneath the ice pack. These strip-chart profiles are the source of data for this study (Figure

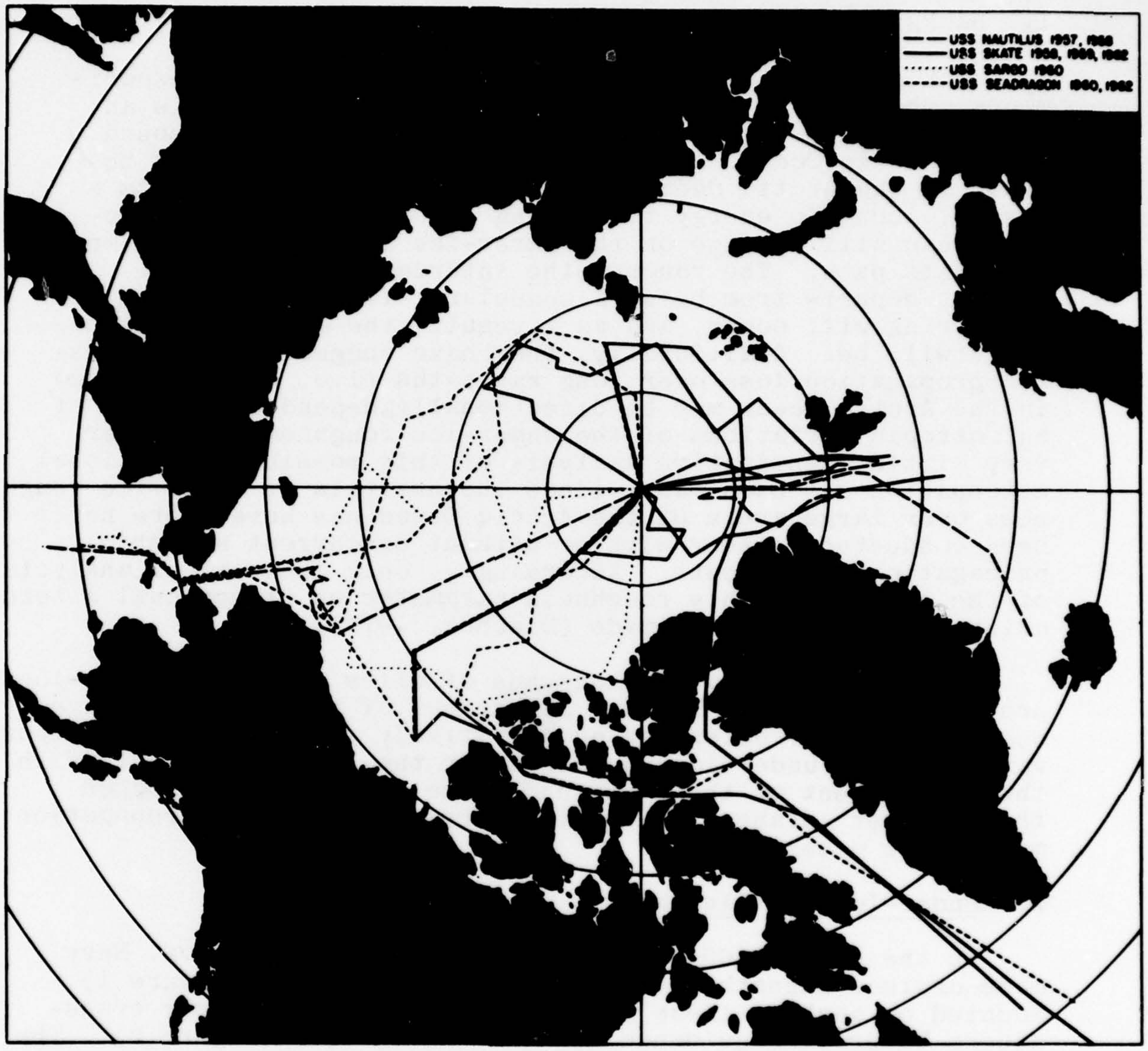

FIGURE 1: Cruise tracks of U. S. nuclear submarines in the Arctic Ocean (after Lyon, 1963).

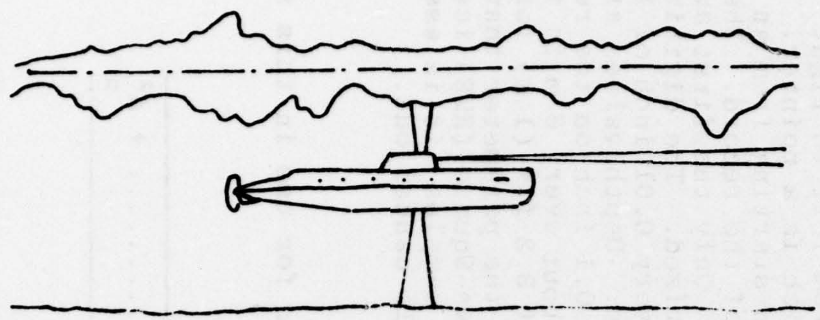

FIGURE 2: Sonar system for cruising under sea ice (after Lyon, 1963).

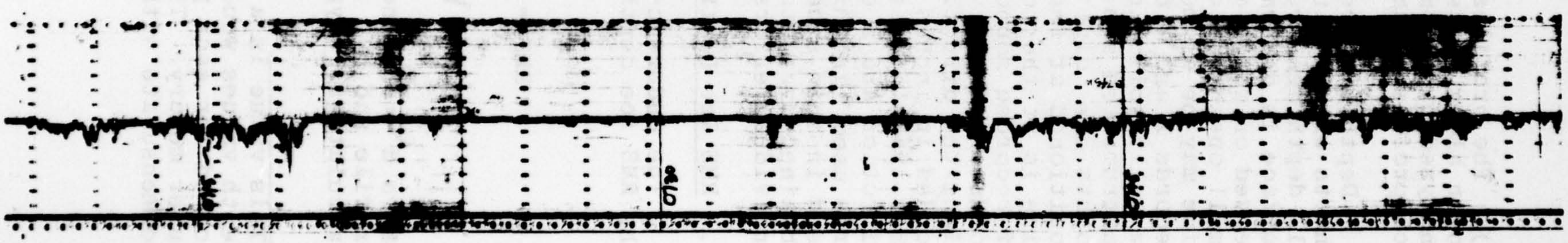

FIGURE 3: A 4-nautical mile submarine sonar under-ice segment recorded in the Chukchi Sea near Pt. Hope.

3). The profiles, which reflect the under surface of the ice cover along the submarine's course, have been digitized and analyzed by a computer program to extract a variety of under-ice profile parameters useful for quantifying ice distribution.

Depth measurements are made directly from the analog charts with a line-follower digitizer. The base from which all depth measurements are made is the water surface; this surface is determined by the characteristic reflection observed on the record when leads or polynyas are present (as small ones frequently are). The error in picking this water line may be as much as ± 1 m (Lyon, 1971). The digitizer records X and Y data values along the profile by means of manually following the profile, from left to right, with an instrumented arm at the end of which is a pointer. The data points are digitized without sign starting from an origin positioned at the left-hand side of the record. The water-line is at the top of the record. Only the first arrivals of recorded sound energy are digitized. The digitizer records one depth value, (Y), for every 0.01 inch of X-travel along the direction of the profile. Depth values are recorded in inches in increments of 0.1 inch on the record. This translates to a data point about every 6 m in the X-direction and a depth increment of 3.2 ft* (1 m) for the records used in this work. Because the parameter that is being used in this study is the Root-Mean-Square (RMS) ice depth obtained over statistically large samples, it is assumed that individual errors of ice depth will cancel out.

3. RMS Ice Depth

The under-ice parameter chosen for use in this study is the RMS ice depth defined as

$$\mathrm{RMS} = \sqrt{\frac{d_1^2 + d_2^2 + \ldots\ldots\ldots\ldots + d_n^2}{n}}$$

where d = the individual depth value recorded from the analog profile and n = the number of such values used in an RMS calculation. Typically, between 3000 and 3500 data points

*This value is a compromise. Greater precision in digitizing depth values would have reduced the number of data points recorded for each profile segment owing to the size of the computer memory. The present precision, however, appears to be commensurate with the analysis being conducted.

(depth values) were used for each RMS depth calculation. This quantity of points was derived from a profile segment averaging eight nautical miles in length, the length being dependent upon the submarine speed. A number of such adjacent segments were used to develop a population for the statistical analysis that follows.

The RMS depth parameter has been chosen primarily because of its value to under-water acoustic studies in the Arctic (Buck, 1975; Lyon, 1976). Additionally, however, the RMS ice depth would appear to be a good indicator of overall ice deformation for a given ice surface area since any significant departure from the undeformed equilibrium ice depth over the Arctic Ocean (about 3 m) can only occur through building ice ridges and keels or opening of leads and polynyas. RMS ice depth correlates well, for example, with "ice ridging intensity," the ice deformation indicator discussed by Hibler _et al_. (1974) (Hibler 1976).

The data used for this work were collected on three submarine cruises (see Figure 1). The USS SARGO collected data during February 1960 and two cruises were made by the USS SEADRAGON during the summers of 1960 and 1962. Selected RMS ice depth values from each cruise are plotted on Figure 4. From this plot, a general trend of increasing RMS ice depth from West to East appears, with maximum values occurring along the Canadian Archipelago. Comparison of these data distributions with the distributions of "ridging intensity" values of Hibler _et al_. (1974) in the Western Arctic Basin shows that the RMS ice depth values can be well delineated by the three ice ridging provinces which they call Beaufort-Chukchi, West Central Arctic Basin and Archipelago. Since the data of Hibler _et al_. (1974) were recorded a decade after the submarine data were gathered, a stable pattern of ice deformation provinces over time is suggested.

4. Geographical and Temporal Variations of RMS Ice Depth

Cursory examination of Figure 4 suggests that the variation of RMS ice depth is greater going from place to place during the same time period than it is at the same place over time. This has been examined statistically in a preliminary manner. Several profile segments representative of different areas of the Arctic Ocean and ranging from 50 to 250 miles in length were selected from each of the three cruises. They were chosen so that they would, as much as possible, be approximately equidistant from the other segments of the same cruise and would, where possible, intersect the track of one or both of the other cruises. Those segments are labelled A-D for the USS SARGO 1960 cruise, J-M for the USS SEADRAGON 1960 cruise and E-I for the USS SEADRAGON 1962 cruise. Their approximate positions are given in Table 1. Numerous RMS ice depth values, each computed from approximately 3500 depth values, have been listed in Table 2. The

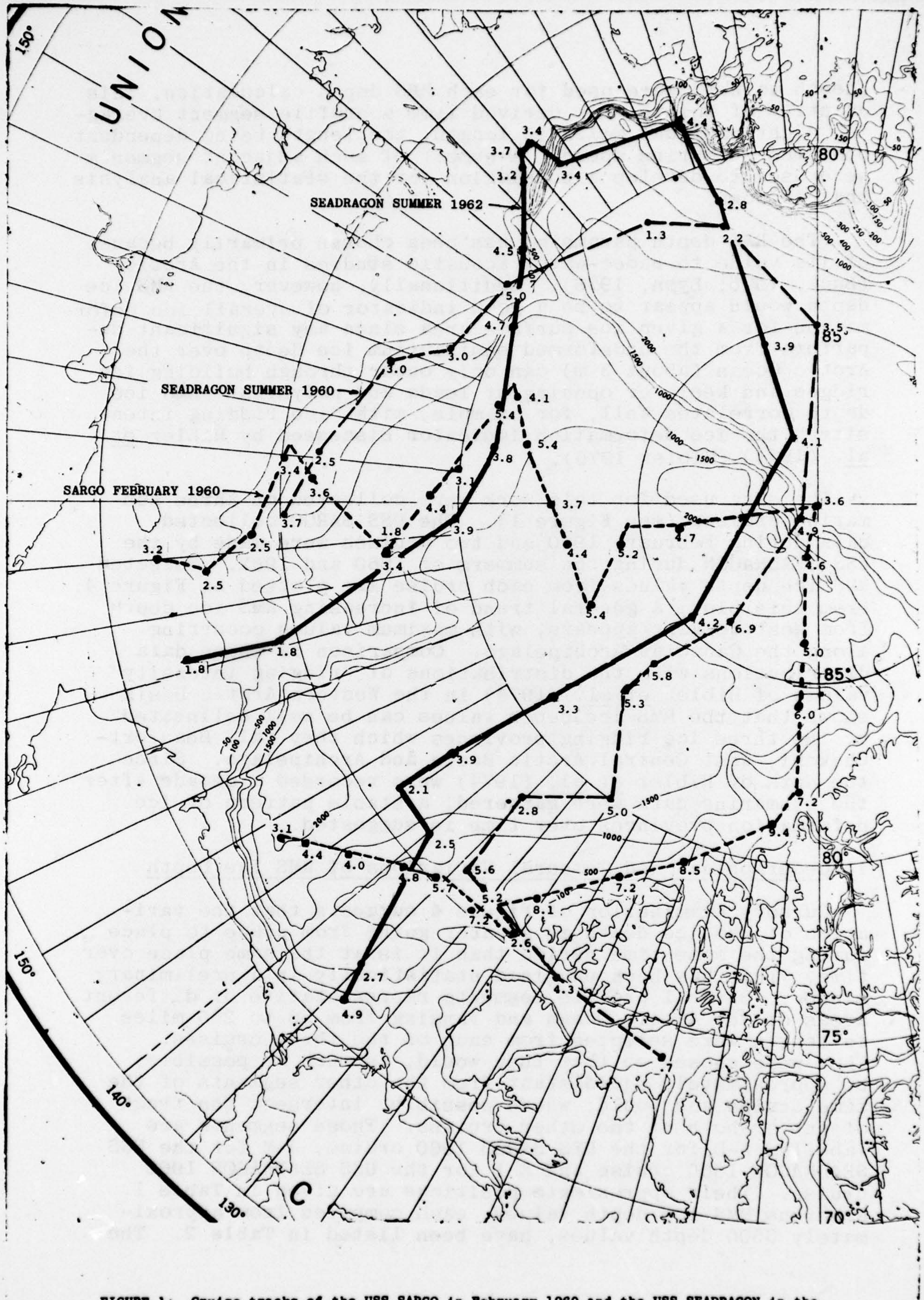

FIGURE 1: Cruise tracks of the USS SARGO in February 1960 and the USS SEADRAGON in the summers of 1960 and 1962. A sampling of RMS ice depths (m) along each track is included. Each data point was derived from a segment of under-ice profile approximately 8 nautical miles in length.

TABLE 1: Approximate Positions of Profile Segments Used for Statistical Analysis

CRUISE	SEGMENT	POSITION
SARGO 60	A	75°N, 175°E - 76°N, 177°E
	B	77°N, 177°W - 78°N, 177°W
	C	79°N, 178°E - 81°N, 165°E
	D	86°N, 120°W - 90°N, 170°W
SEADRAGON 62	E	78°N, 172°W - 80°N, 180°W
	F	81°N, 170°E - 81°N, 155°E
	G	81°N, 155°E - 78°N, 138°E
	H	82°N, 105°E - 84°N, 106°E
	I	86°N, 105°E - 90°N, 105°E
SEADRAGON 60	J	88°N, 125°W - 90°N, 125°W
	K	85°N, 100°E - 83°N, 112°E
	L	80°N, 140°E - 80°N, 147°E
	M	76°N, 173°E - 75°N, 177°W

TABLE 2: Statistical Comparison of RMS Ice Depth Values for Adjacent Segments Recorded During the Same Cruise

	SARGO 60				SEADRAGON 62					SEADRAGON 60			
Segment	A	B	C	D	E	F	G	H	I	J	K	L	M
	3.4	3.4	3.1	4.7	1.8	3.8	4.7	2.8	4.1	4.9	3.5	5.0	2.5
	2.4	4.1	3.3	5.1	2.1	3.1	4.9	4.4	5.0	4.6	3.1	2.9	2.6
	2.7	5.6	2.9	5.2	2.7	3.2	4.9	3.7	5.5	4.7	2.9	2.8	3.2
	4.6	3.9	2.1	3.9	2.8	3.1	4.3	3.3	5.3	5.2	2.7	2.9	3.7
	3.6	5.4	3.7	5.1	2.2	3.8	4.6	2.1	4.6	5.1	3.7	2.8	3.4
	2.6	4.6	3.7	4.6	2.4	4.1	3.3	3.4	4.7	5.6	4.0	3.8	4.9
	4.3	4.1	3.4	4.6	2.6	4.5	4.8	3.6	3.7		3.0	3.4	3.6
	2.5	3.3	3.0	4.9	2.6	4.4	5.5	4.7	4.1		2.9	3.7	3.8
	3.5	3.5	3.1	4.0	2.4	3.4	6.0	4.3	3.5		3.2	3.6	3.7
	2.2	4.7	3.5	4.8	2.4	4.7	3.6	4.2	4.0		2.2	3.8	3.7
	3.5	3.6	4.5	5.3	2.0		4.5	4.7	4.8			3.2	3.7
	3.2		4.4	4.6	3.4			3.9	3.2			3.0	
	4.4		3.3	3.6	3.9				3.4				
	3.6		3.2	3.6					5.3				
			5.4	3.6									
				4.0									
				5.2									
		Different	Different	Different		Different	Different	Different	Same		Different	Same	Same

specific number of RMS values computed was a compromise between the desire to have many values for a statistical analysis and the need to keep stationarity within the time (or space) series.

It has been assumed that the tabulated RMS depth values for each segment come from a normal population. This is believed to be true because, although the individual depth values are not normally distributed, the central limit theorem states that the population of a sample means from a non-normal population approximates a normally distributed population (see, for example, Mack, 1967). Additionally, it has been assumed that the variances of the segment populations are equal (the standard deviation of the variances of the 13 segments is 0.16 about a mean variance of 0.45). Accordingly, it appears valid to use a "Student" two-sample t-test to compare the profile segments. When this test is used to compare RMS ice depths for adjacent segments of the same cruise (Table 2), seven out of ten segment population pairs used in the comparison are different at the 5% probability level (i.e., there is a 95% probability that the compared populations are different). On the other hand, when comparison is made between intersecting profile segments of different cruise tracks (Table 3), five out of seven segment population pairs used in this comparison are the same at the 5% probability level. Simply stated, the analysis implies that for the 1960-62 period there is significant variation in the RMS under-ice depth from place to place during the same time period but at different times at the same place, the RMS under-ice depth does not vary significantly. This result appears to have important ramifications for future under-ice acoustic studies in the Arctic.

5. Frequency of Occurrence of Ice of Different Depths

There are a number of other under-ice profile parameters that are valuable for Arctic sea ice research. Another such parameter that has been developed during the past research is the frequency of occurrence of ice at different depths across the Arctic Ocean. These frequency of occurrence data are particularly useful in modeling the Arctic sea ice. Examples of these data are presented in Figures 5, 6 and 7 and are plotted as histograms of ice depths observed during the above three cruises. From these plots it can be seen that for the 1960-62 period there is 15% open water in the summer and 2% during the winter. Additionally, it is noted that the percentage of ice found in each thickness class varies only a few percent between winter and the following summers.

TABLE 3: Statistical Comparison of RMS Ice Depth Values for Intersections of the Different Cruise Tracks

	SARGO-SEADRAGON 60				SARGO-SEADRAGON 62				SEADRAGON 60-SEADRAGON 62					
Segment	D	J	M	A	C	F	I	D	I	J	K	H	G	L
	4.7	4.9	2.5	3.4	3.1	3.8	4.1	4.7	4.1	4.9	3.5	2.8	4.7	5.0
	5.1	4.6	2.6	2.4	3.3	3.1	5.0	5.1	5.0	4.6	3.1	4.4	4.9	2.9
	5.2	4.7	3.2	2.7	2.9	3.2	5.5	5.2	5.5	4.7	2.9	3.7	4.9	2.8
	3.9	5.2	3.7	4.6	2.1	3.1	5.3	3.9	5.3	5.2	2.7	3.3	4.3	2.9
	5.1	5.1	3.4	3.6	3.7	3.8	4.6	5.1	4.6	5.1	3.7	2.1	4.6	2.8
	4.6	5.6	4.9	2.6	3.7	4.1	4.7	4.6	4.7	5.6	4.0	3.4	3.3	3.8
	4.6		3.6	4.3	3.4	4.5	3.7	4.6	3.7		3.0	3.6	4.8	3.4
	4.9		3.8	2.5	3.0	4.4	4.1	4.9	4.1		2.9	4.6	5.5	3.7
	4.0		3.7	3.5	3.1	3.4	3.5	4.0	3.5		3.2	4.7	6.0	3.6
	4.8		3.7	2.2	3.5	4.7	4.0	4.8	4.0		2.2	4.3	3.6	3.8
	5.3		3.7	3.5	4.5		4.8	5.3	4.8			4.2	4.5	3.2
	4.6			3.2	4.4		3.2	4.6	3.2			4.7		3.0
	3.6			4.4	3.3		3.4	3.6	3.4			3.9		
	3.6			3.6	3.2		5.3	3.6	5.3					
	3.6				5.4			3.6						
	4.0							4.0						
	5.2							5.2						
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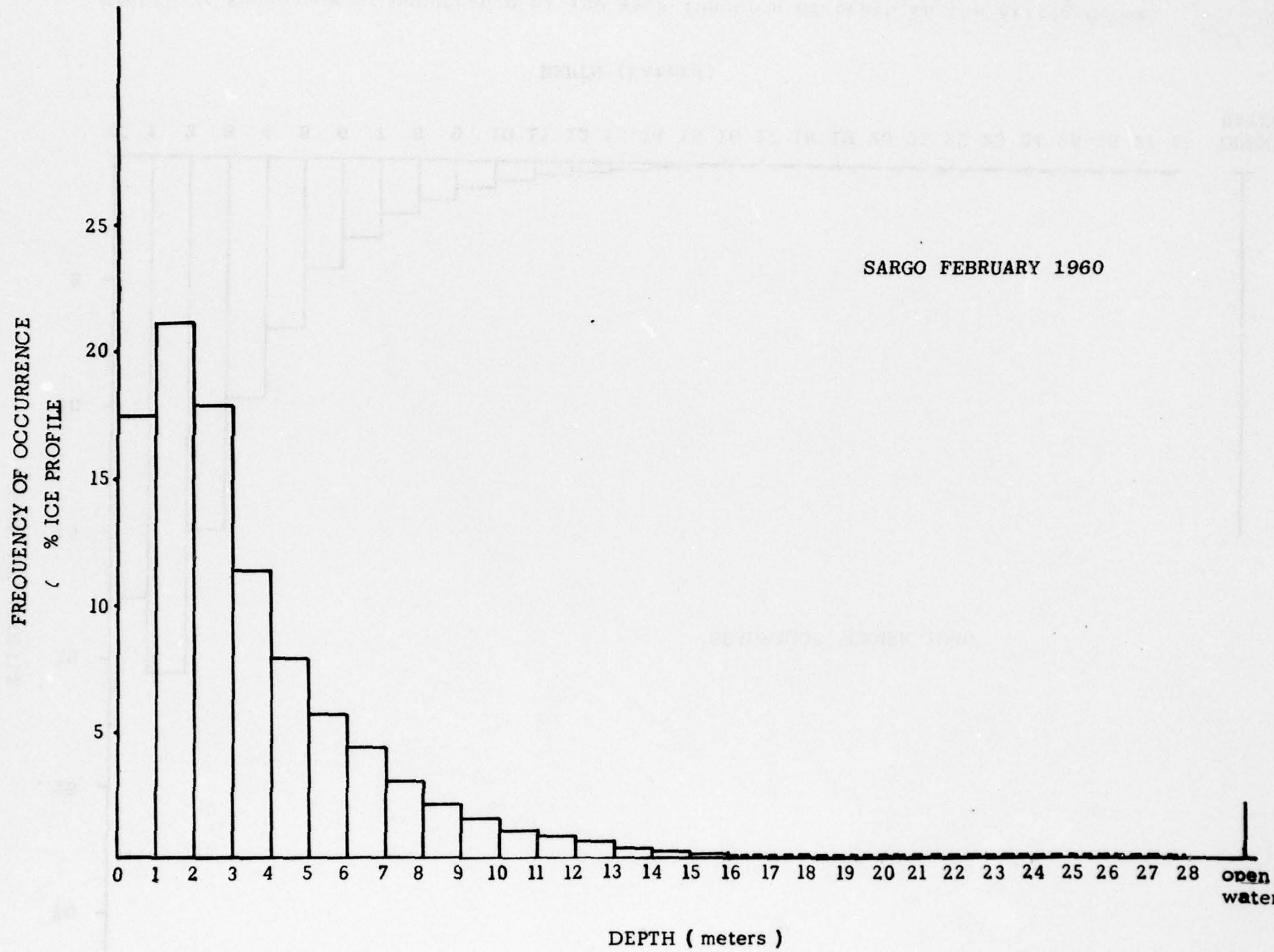

FIGURE 2: Frequency of occurrence of ice as a function of depth in the Arctic Ocean. The histogram is the summation of the histograms derived from each of the first 22 profile locations shown in Figure 1 going clockwise and represents an estimate of the probability of randomly locating ice of a given depth in that portion of the Arctic Ocean covered by the cruise track.

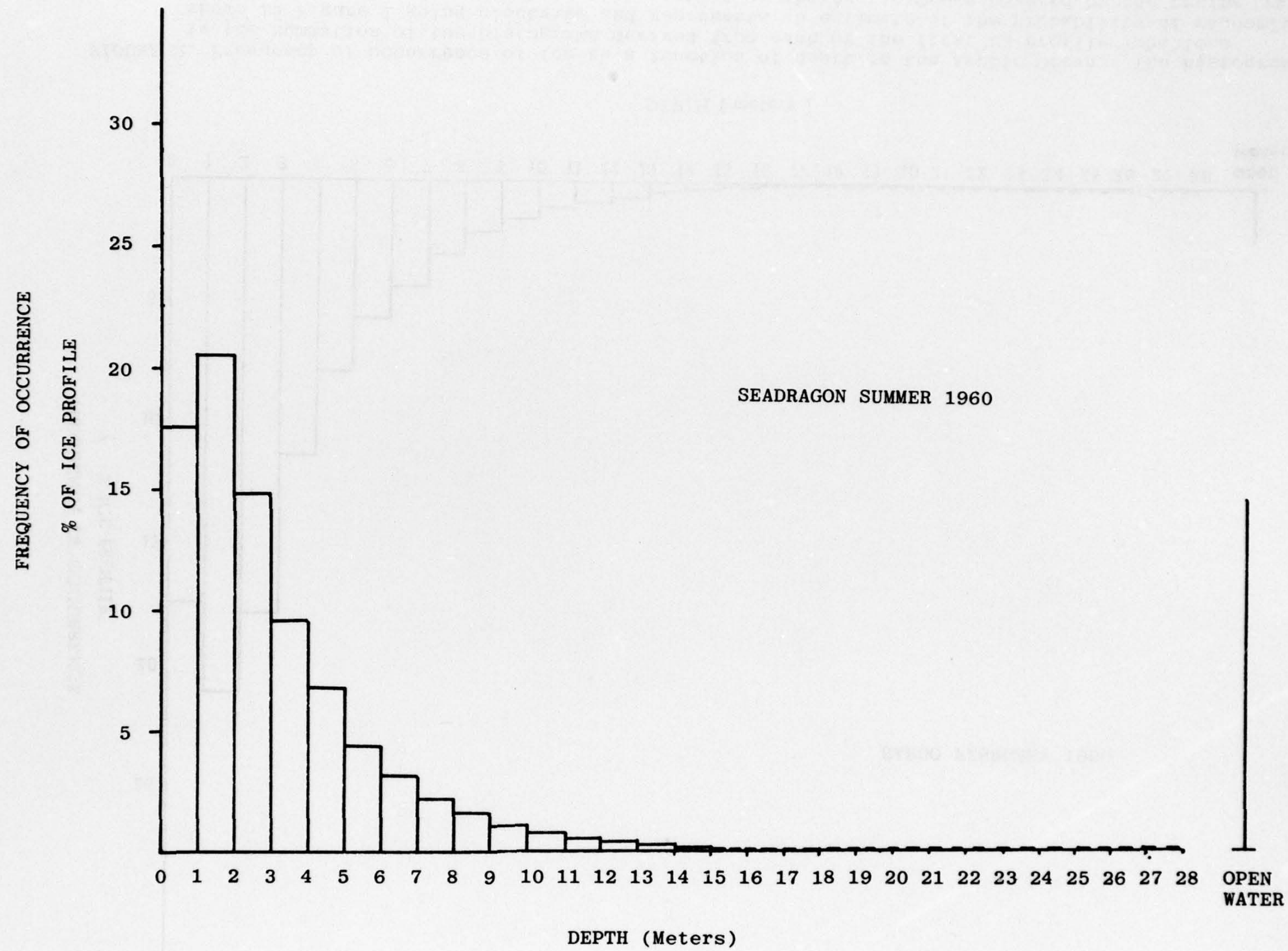

FIGURE 3: Frequency of occurrence of ice as a function of depth in the Arctic Ocean. The histogram is the summation of the histograms derived from each of the 18 profile locations shown in Figure 1 and represents an estimate of the probability of randomly locating ice of a given depth in that portion of the Arctic Ocean covered by the cruise track.

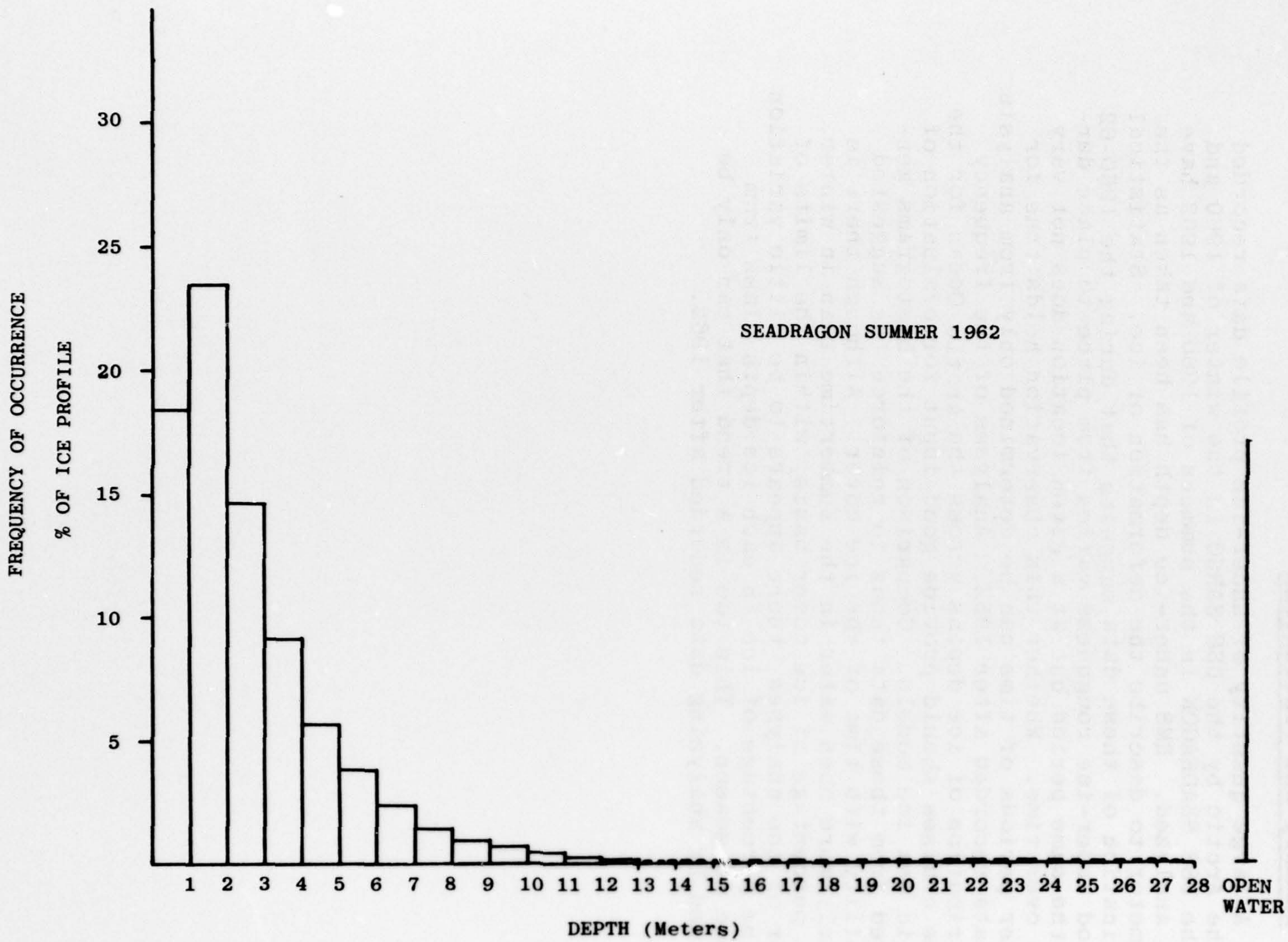

FIGURE 4: Frequency of occurrence of ice as a function of depth in the Arctic Ocean. The histogram is the summation of the histograms derived from each of the 22 profile locations shown in Figure 1 and represents an estimate of the probability of randomly locating ice of a given depth in that portion of the Arctic Ocean covered by the cruise track.

6. Summary and Conclusions

A large quantity of under-ice profile data recorded in the Arctic by the USS SARGO in the winter of 1960 and by the USS SEADRAGON in the summers of 1960 and 1962 have been analyzed. RMS under-ice depth has been taken as the parameter to describe the deformation of ice. Statistical examination of these data suggests that during the 1960-62 period under-ice roughness varies from place to place during the same period but at a given location does not vary much over time. Whether this observation holds true for longer periods of time can be determined only from analysis of data recorded after 1962. Analyses of the frequency distribution of ice depths across the Arctic Ocean for the three cruises should provide good input for evaluation of Arctic sea ice models. Comparison of the histograms generated from these data tends to reinforce the suggested stability with time of the ice cover. Although there is clearly more open water in the summertime than in winter, on a percentage of ice cover basis, within the limits of error of the analyses, there appears to be little variation of the percentage of ice in each ice depth class from season to season. This too is a trend that can only be checked by analyzing data recorded after 1962.

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13. ABSTRACT

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There is no limitation on the length of the abstract. However, the suggested length is from 150 to 225 words.

14. *KEY WORDS:* Key words are technically meaningful terms or short phrases that characterize a report and may be used as index entries for cataloging the report. Key words must be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location, may be used as key words but will be followed by an indication of technical context. The assignment of links, rules, and weights is optional.

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78